Quantum Optical Coherence Tomography

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http://www.bu.edu/qil/

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

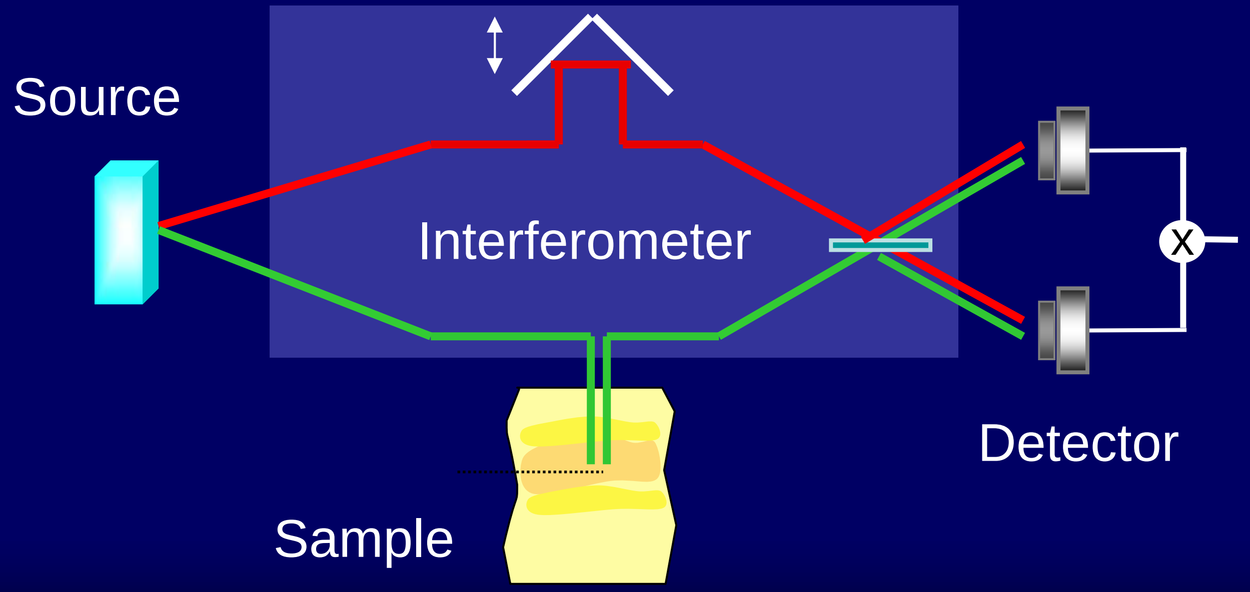
Quantum Optical Coherence Tomography

= Axial imaging (ranging) by use of:

1) 2-photon light in an entangled state,

2) a quantum interferometer,

3) a photon coincidence detector



Outline

1. Two-Photon Imaging
2. QOCT: Prior Work
3. New Results

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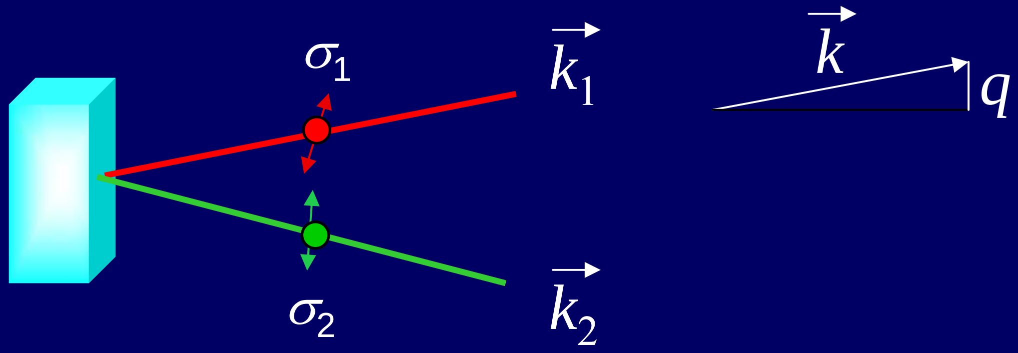
Two-Photon light



$$\mathbf{X} = (q, \omega, \sigma)$$

spatial spectral polarization

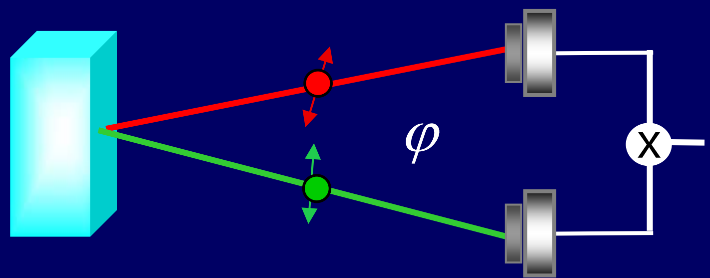
= a state of exactly two photons in multimodes (spatial/spectral/polarization)

$$|\Psi\rangle = \iint d\mathbf{X}_1 d\mathbf{X}_2 \ \underbrace{\varphi(\mathbf{X}_1, \mathbf{X}_2)}\, |1_{\mathbf{X}_1}, 1_{\mathbf{X}_2}\rangle$$

non-separable function ≡ entangled state

Entanglement: Spatial (momentum)
Spectral
Polarization

Measurement of Two-Photon light

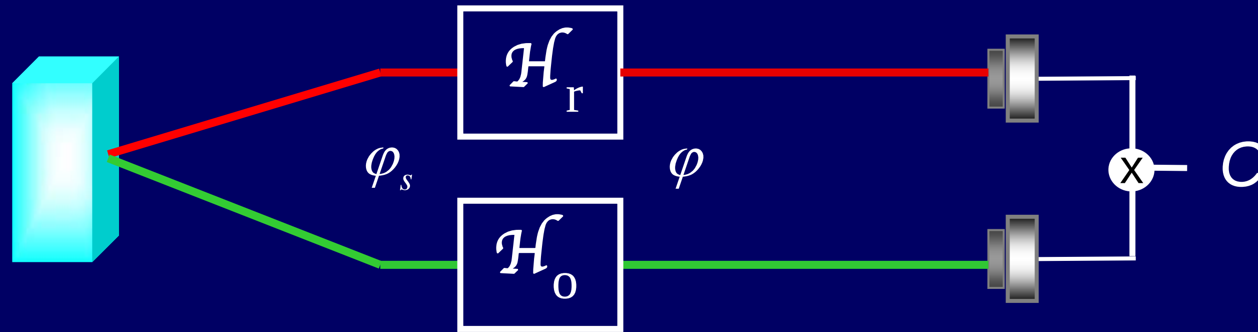


$$C = \iint \left|\varphi\left(\mathbf{X}_1, \mathbf{X}_2\right)\right|^2 \, d\mathbf{X}_1 d\mathbf{X}_2$$

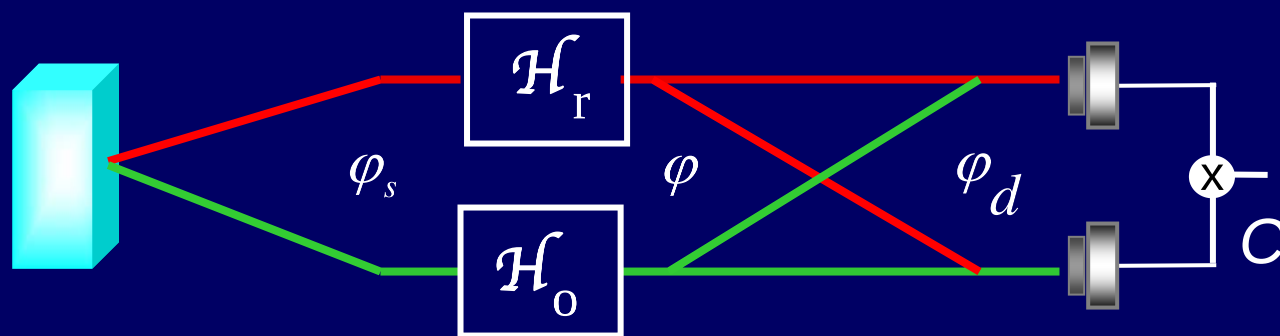
$\varphi\left(\mathbf{X}_1, \mathbf{X}_2\right)$ obeys propagation laws of coherence function (Wolf's equations), although it is not a coherence function

Two Configurations for Metrology / Imaging

A. Direct



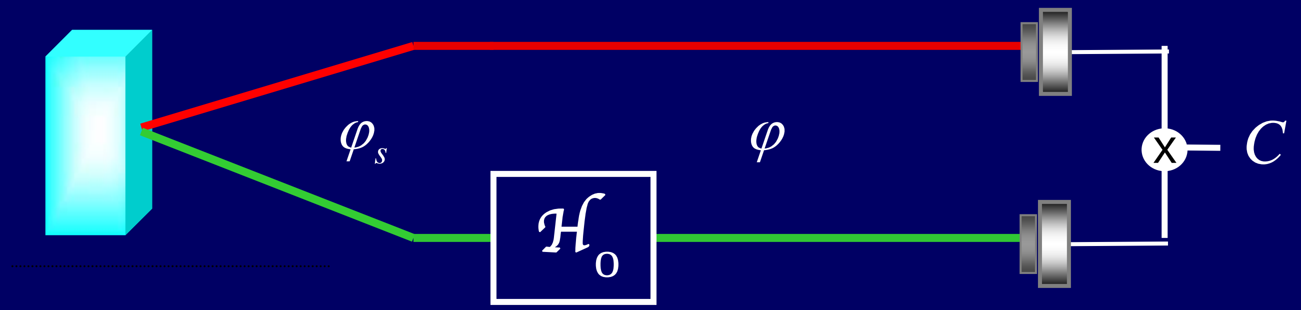
B. Interferometric



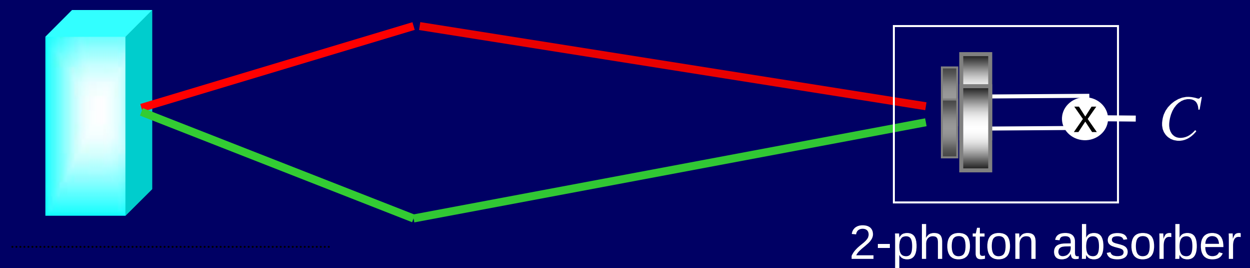
$\mathcal{H}$ = Spatial, spectral, or polarization system

$$\varphi_d(\mathbf{X}_1,\mathbf{X}_2) = \frac{1}{2}\left[\varphi(\mathbf{X}_1,\mathbf{X}_2) - \varphi(\mathbf{X}_2,\mathbf{X}_1)\right]$$

A. Applications of Direct 2-Photon Imaging

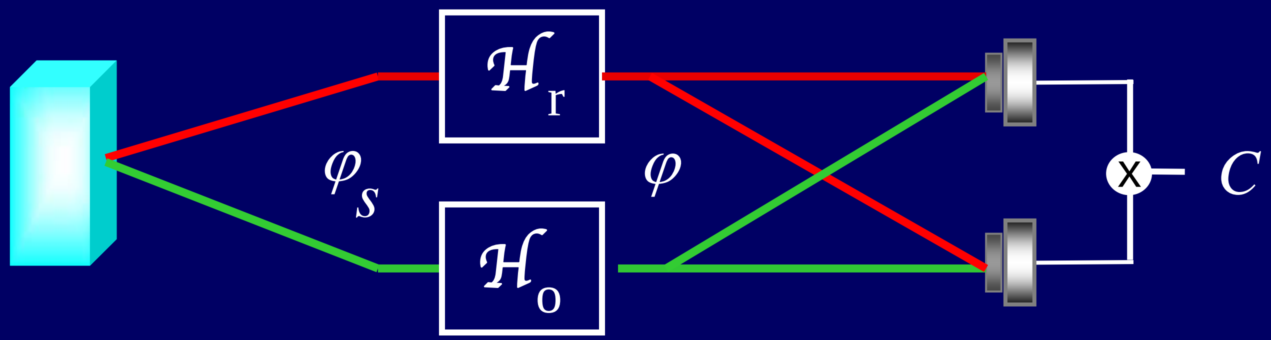


1. Absolute Measurement
2. Ghost Imaging (transverse)



3. 2-Photon Microscopy (transverse)
4. 2-Photon Lithography (transverse)

B. Applications of Interferometric 2-Photon Imaging



$$C = \frac{1}{4}\iint \left| \varphi(\mathbf{X}_1, \mathbf{X}_2) - \varphi(\mathbf{X}_2, \mathbf{X}_1) \right|^2 d\mathbf{X}_1 d\mathbf{X}_2$$

QOCT

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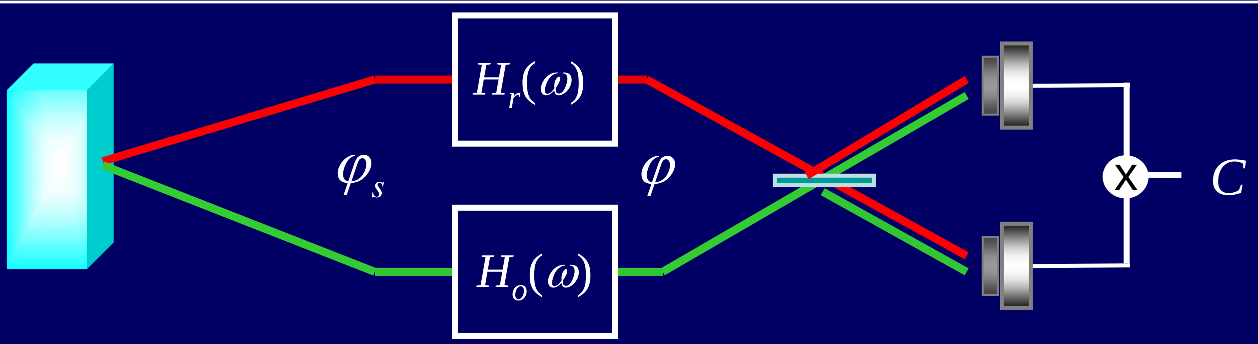
Axial Imaging/Ranging Spectral Modes



$$\varphi_s(\omega_1,\omega_2) = F(\omega_1)\delta(\omega_1+\omega_2-\omega_p) \qquad H_r(\omega) = \mathrm{e}^{-i\omega\tau}$$

$$\varphi(\omega_1,\omega_2) = H_r(\omega_1)H_o(\omega_2)F(\omega_1)\delta(\omega_1+\omega_2-\omega_p)$$

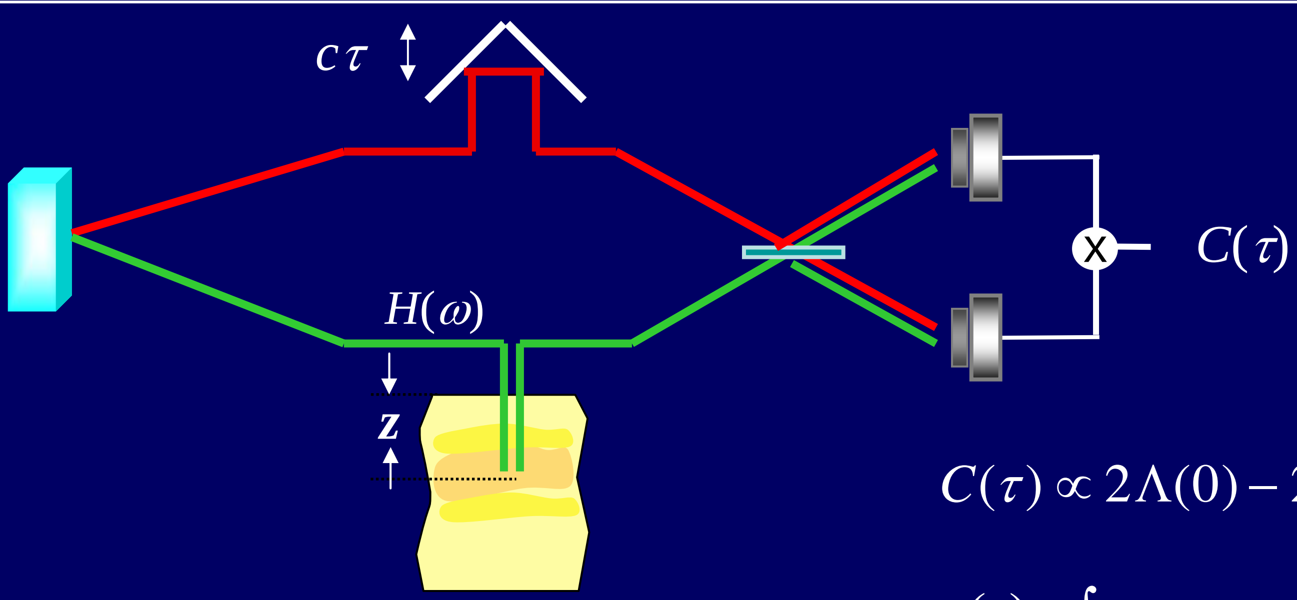
$$C = \frac{1}{4}\iint \left| \varphi(\omega_1,\omega_2) - \varphi(\omega_2,\omega_1) \right|^2 d\omega_1 d\omega_2$$

Interference term in $C \propto$

$$\boxed{H_o(\omega_1)H_o^*(\omega_2)}\, e^{-i(\omega_1-\omega_2)\tau}\delta(\omega_1+\omega_2-\omega_p)F(\omega_1)F^*(\omega_2)$$

i.e., insensitive to even-order dispersion (GVD) in H_o,

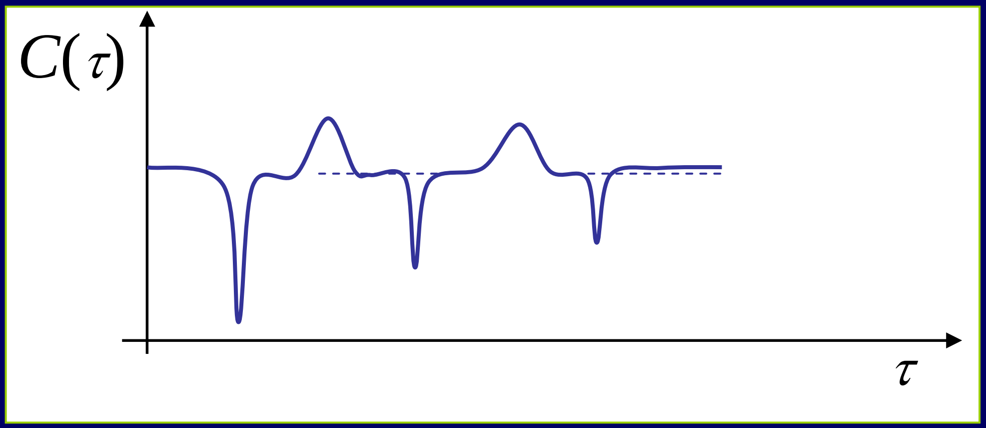
Q-OCT



$$C(\tau) \propto 2\Lambda(0) - 2\,\mathrm{Re}\{\Lambda(2\tau)\}$$

$$\Lambda(\tau) = \int d\Omega H(\omega_o + \Omega) H^*(\omega_o - \Omega) S(\Omega) e^{-i\Omega\tau}$$

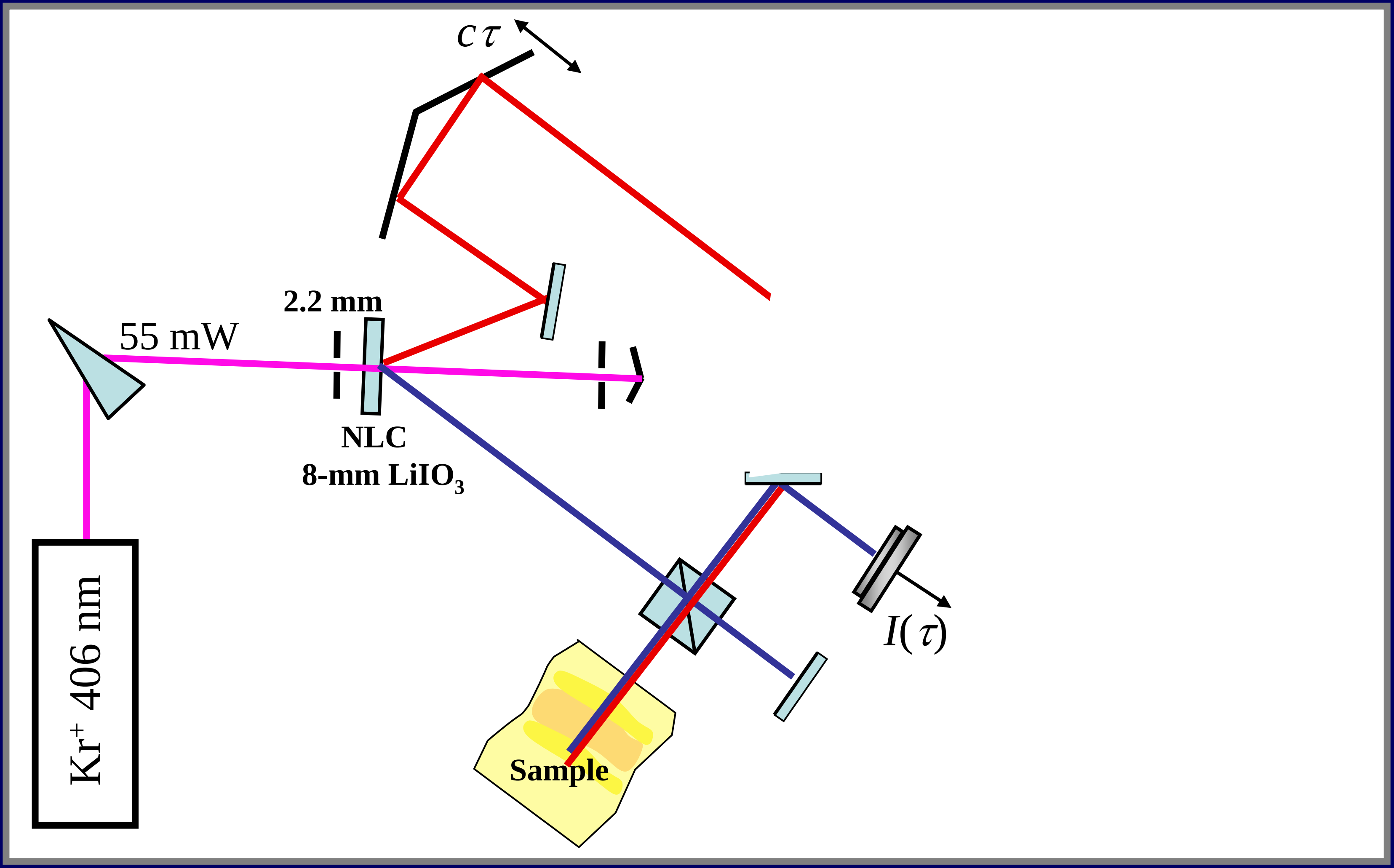
Dispersion-Cancellation



Hong-Ou-Mandel Interferometer

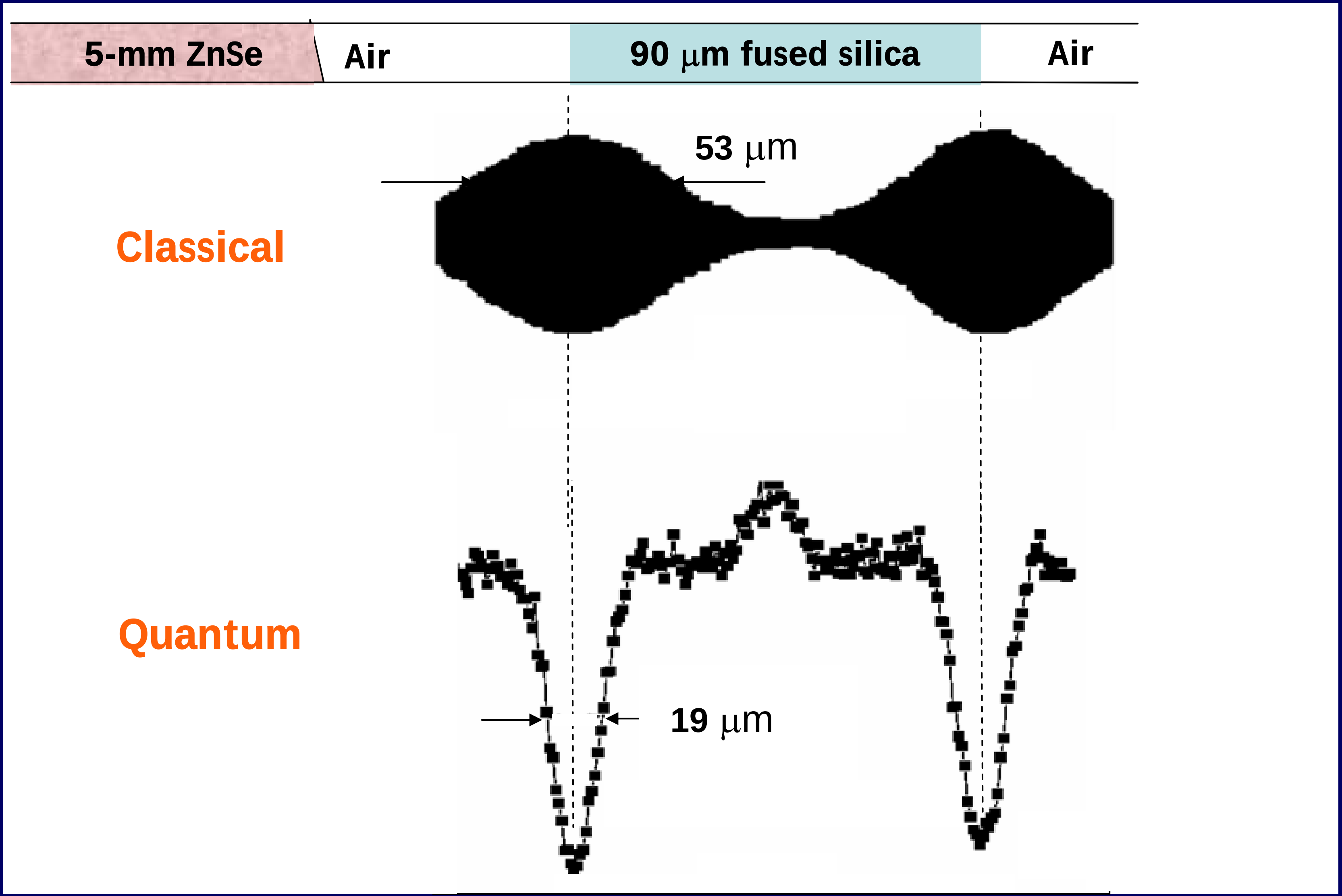
Abouraddy et al. PRA, 053817, 2002

Experimental Setup for Hybrid OCT & QOCT

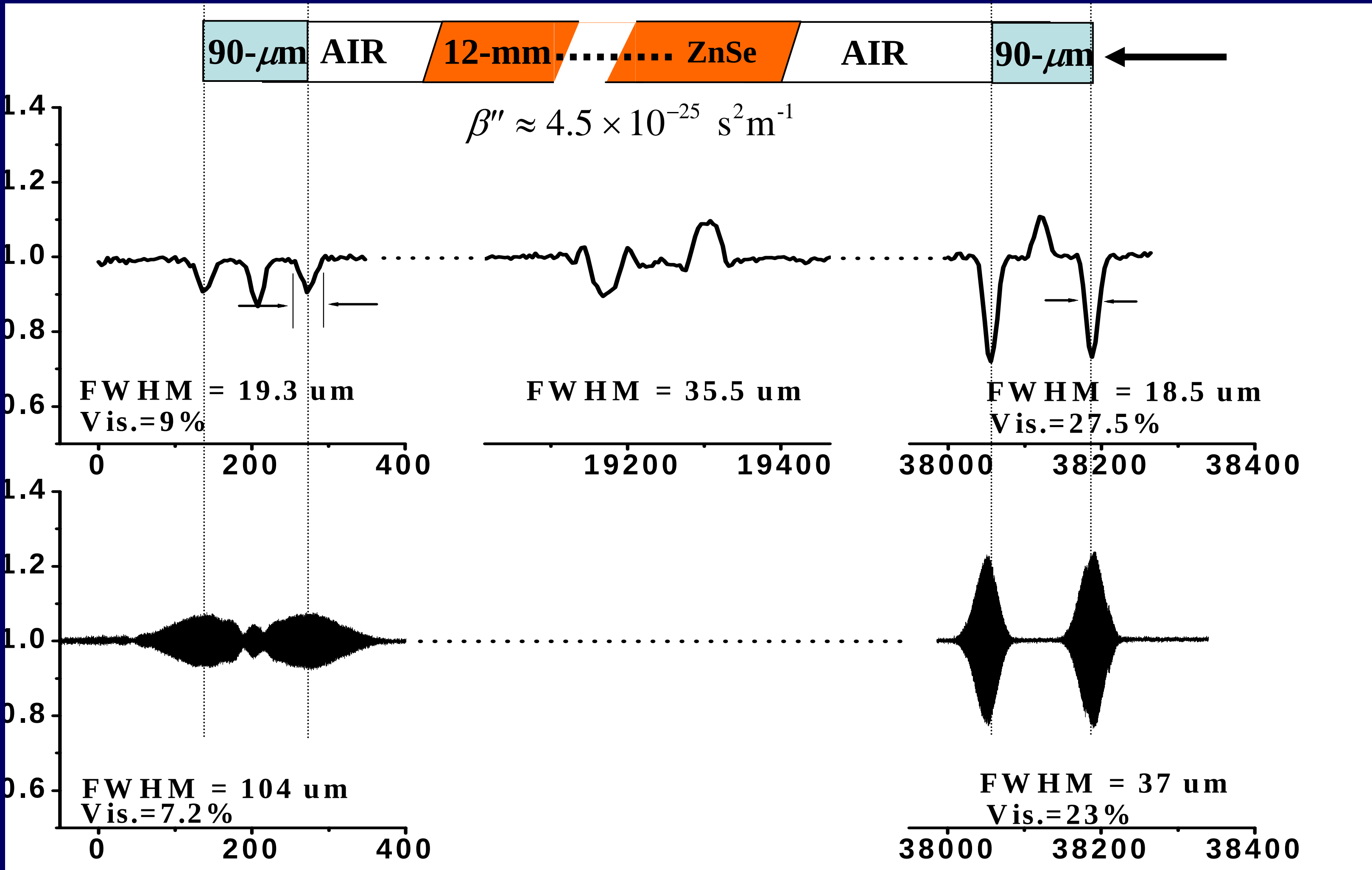


Nasr et al. PRL, 91, August 2003

Two Boundaries + dispersive layer

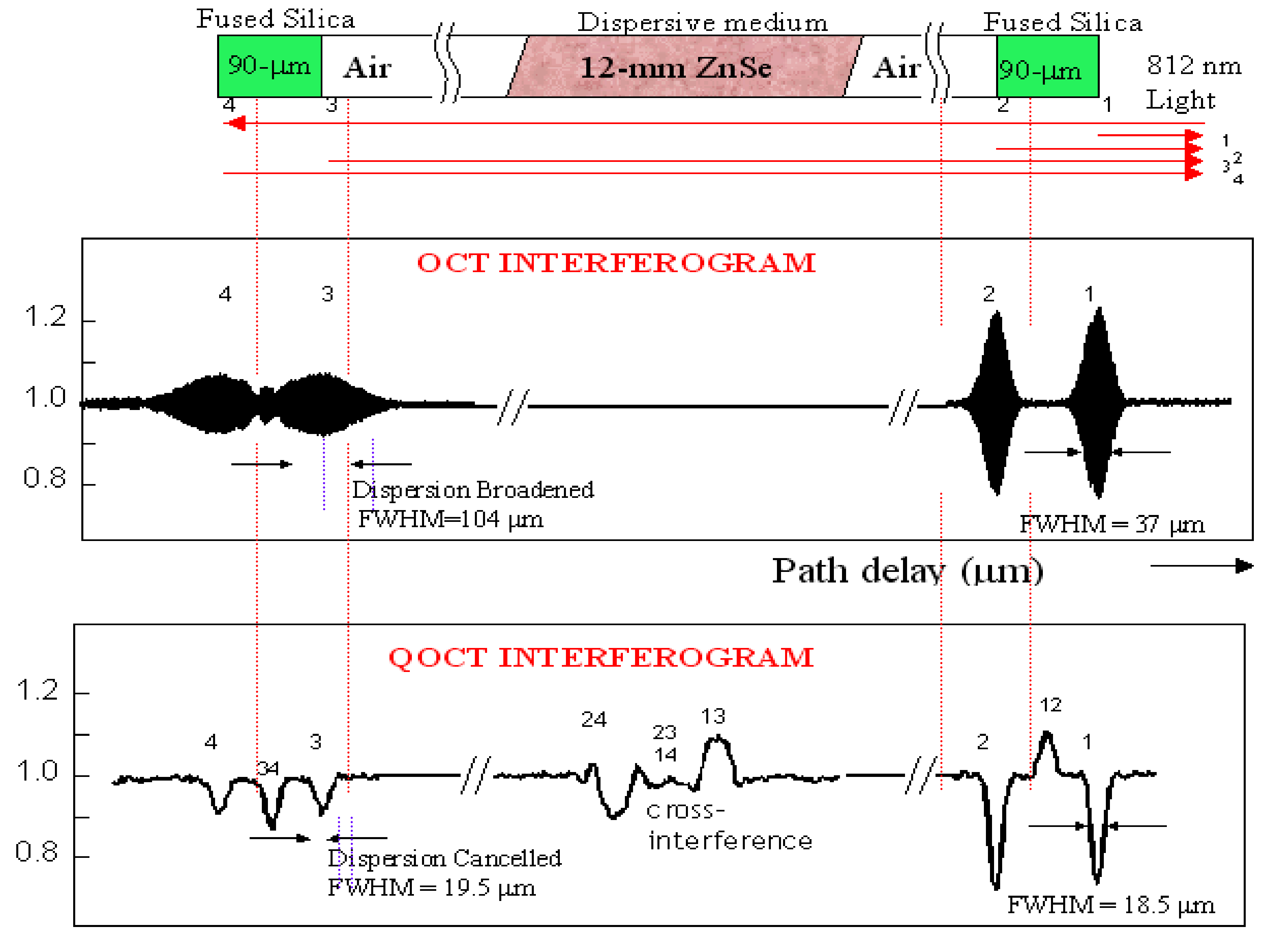


Four Boundaries + dispersive medium in-between



M. B. Nasr *et al.*, Opt. Express **12,** 1353-1362 (2004)

Four Boundaries + dispersive medium in-between



M. B. Nasr *et al.*, Opt. Express **12,** 1353-1362 (2004)

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2. QOCT: Theory & Prior Experimental Work
3. New Results

Goals

Design and build new QOCT system with performance competitive with OCT for acquisition of dispersion-cancelled B-scan images

- Improve efficiency (reduced run time)
- Improve axial resolution
- Include transverse effects & nonplanar samples

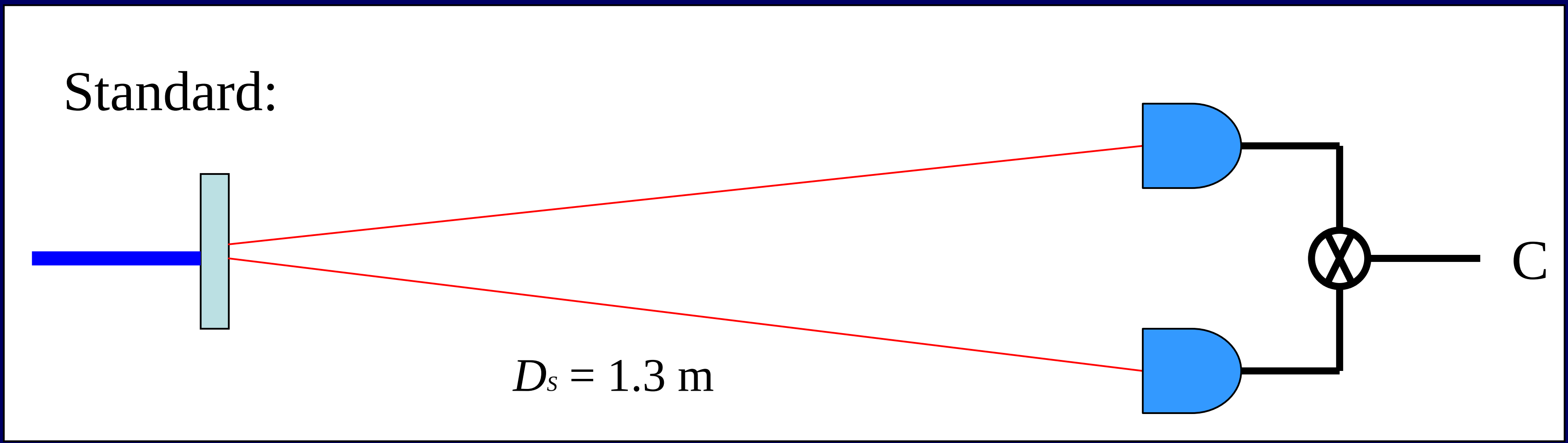
Approach

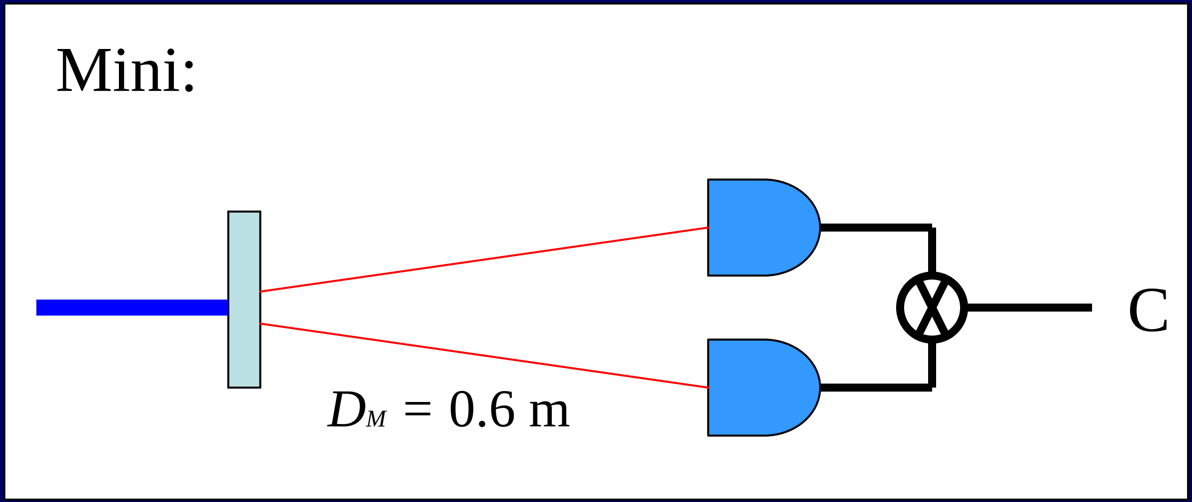
- New source (PPLN)
- New detectors (   )

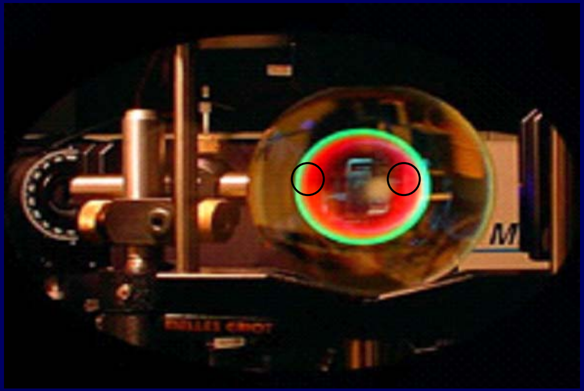
Sergienko

- Improved layout (miniaturization)
- Study of transverse effects

Minitiarization

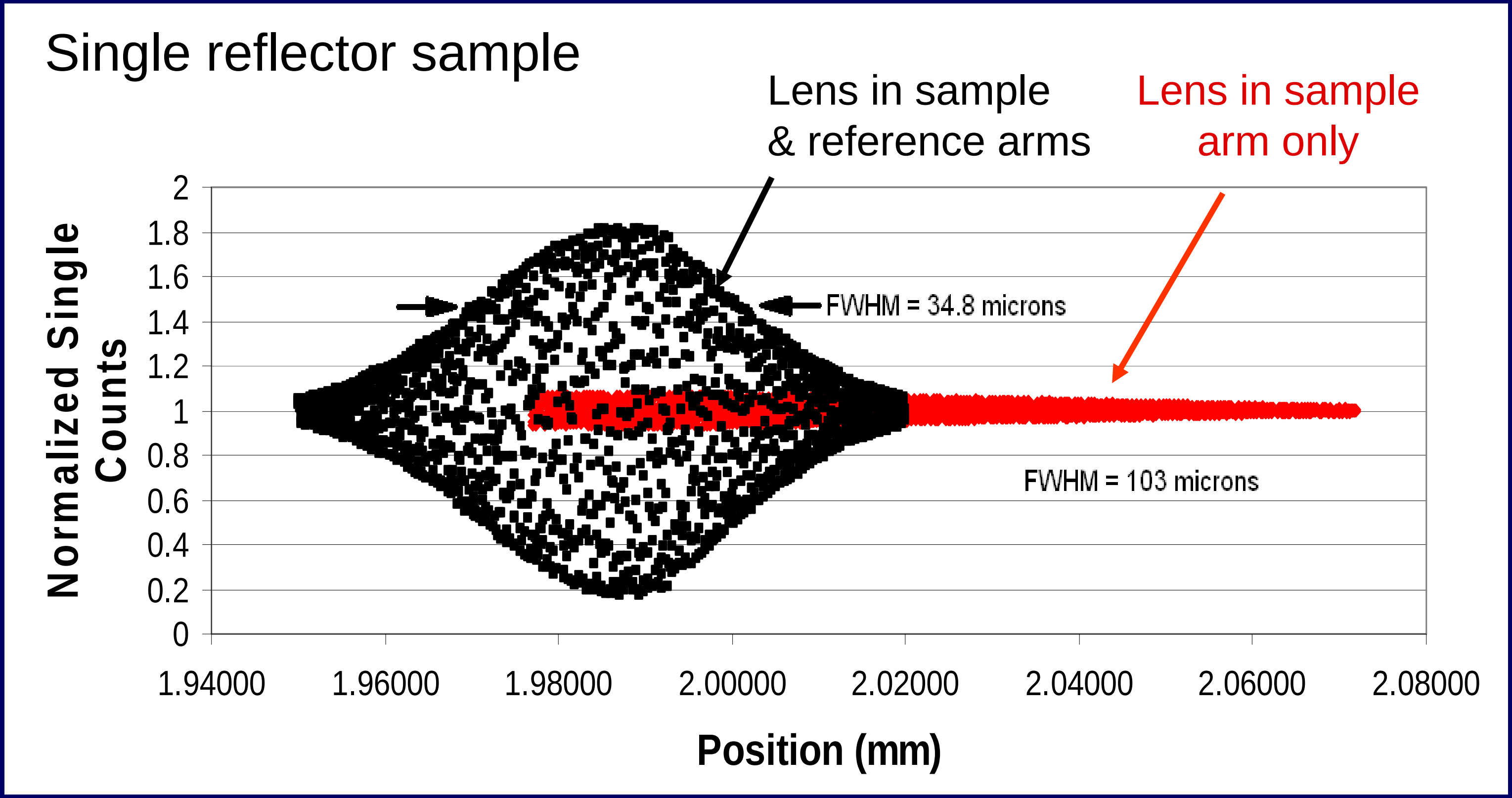




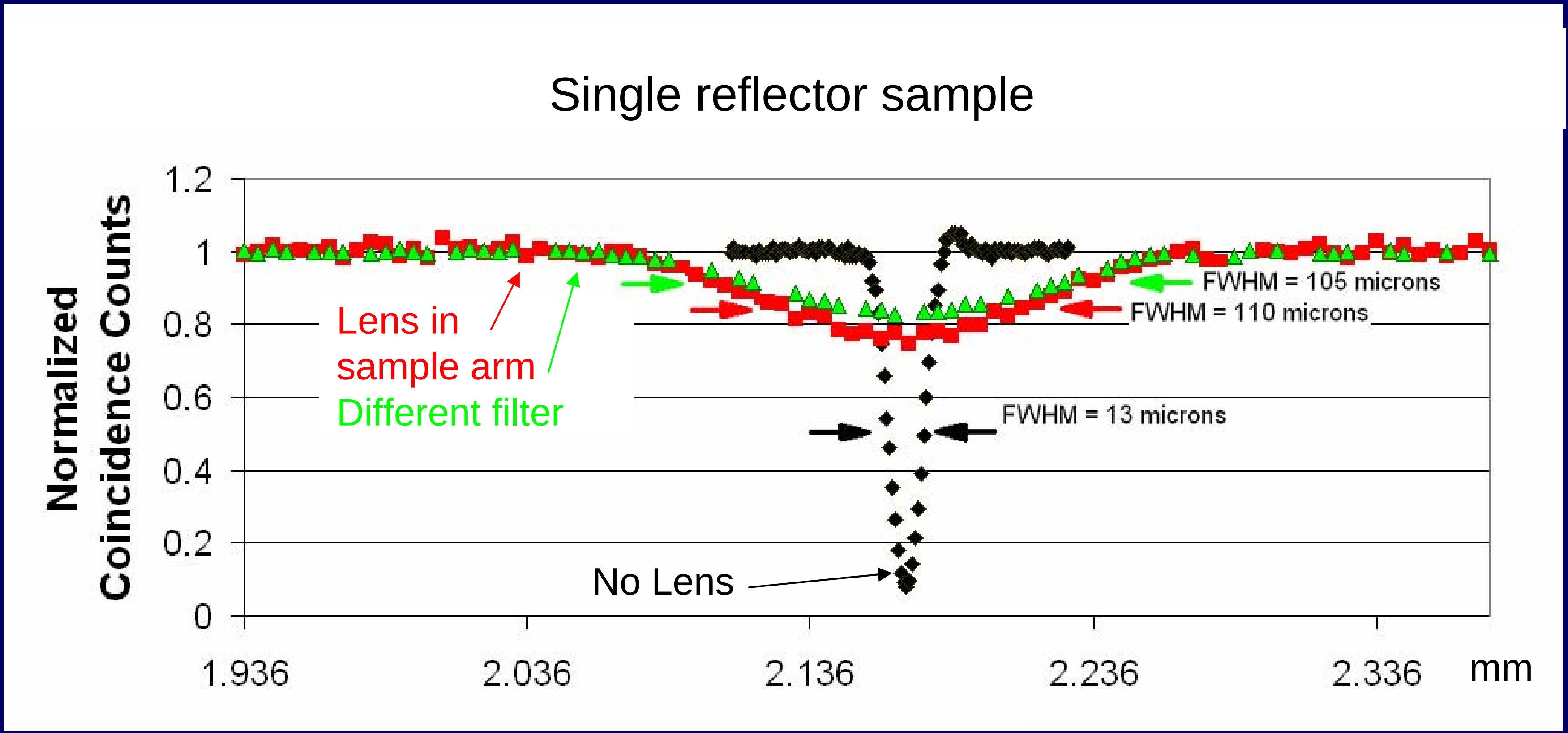


Transverse Effects

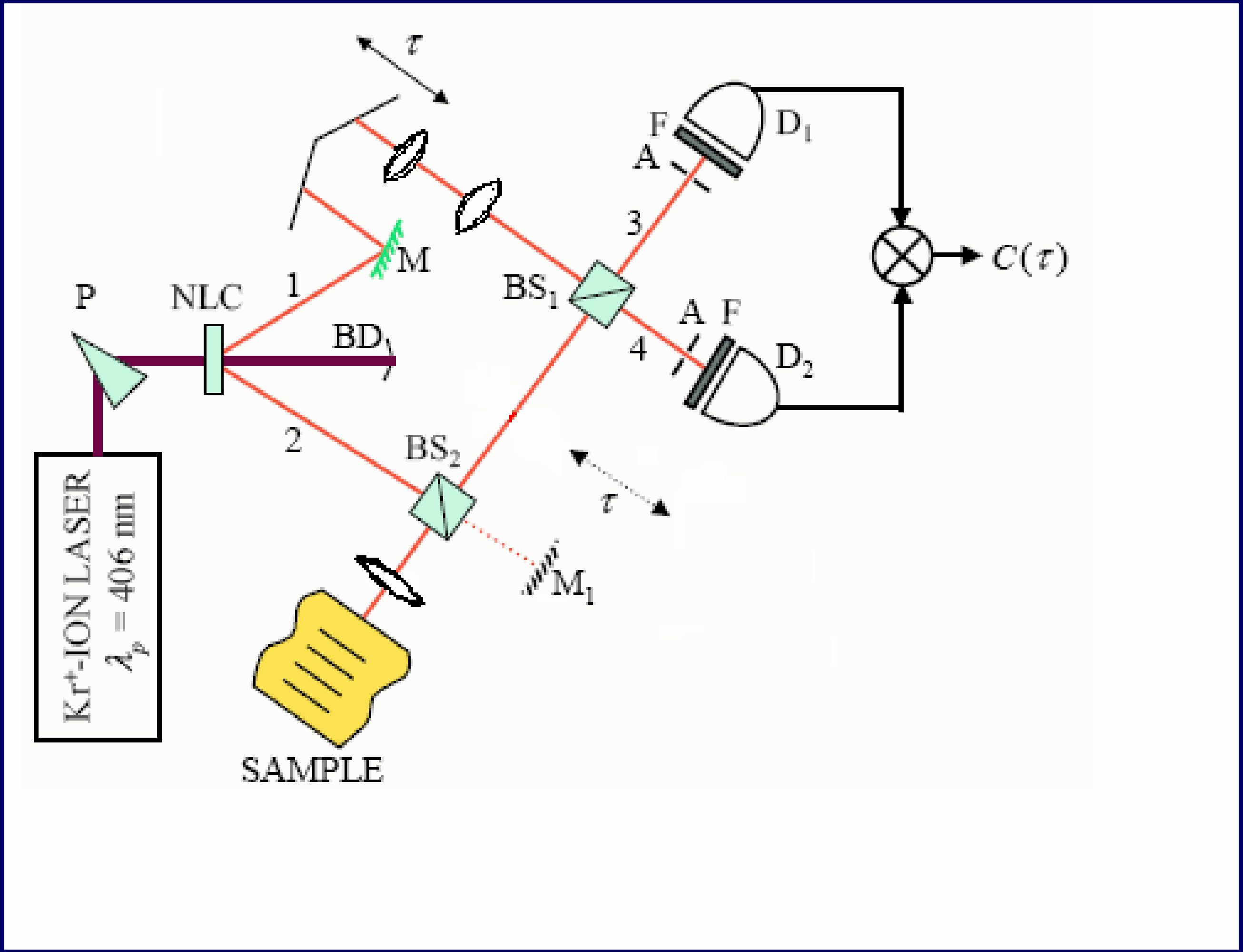
Focusing in Conventional OCT



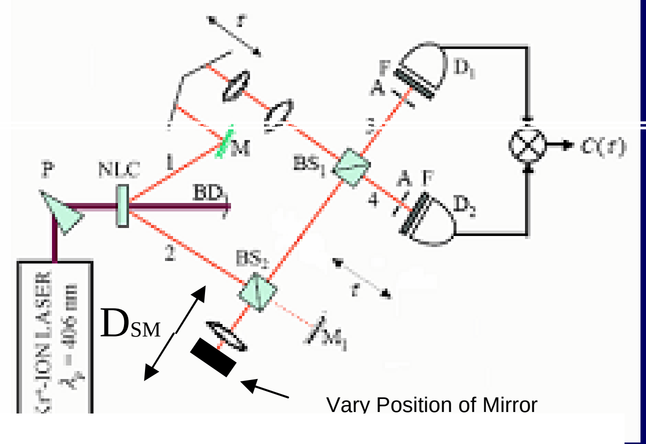
Focusing in QOCT



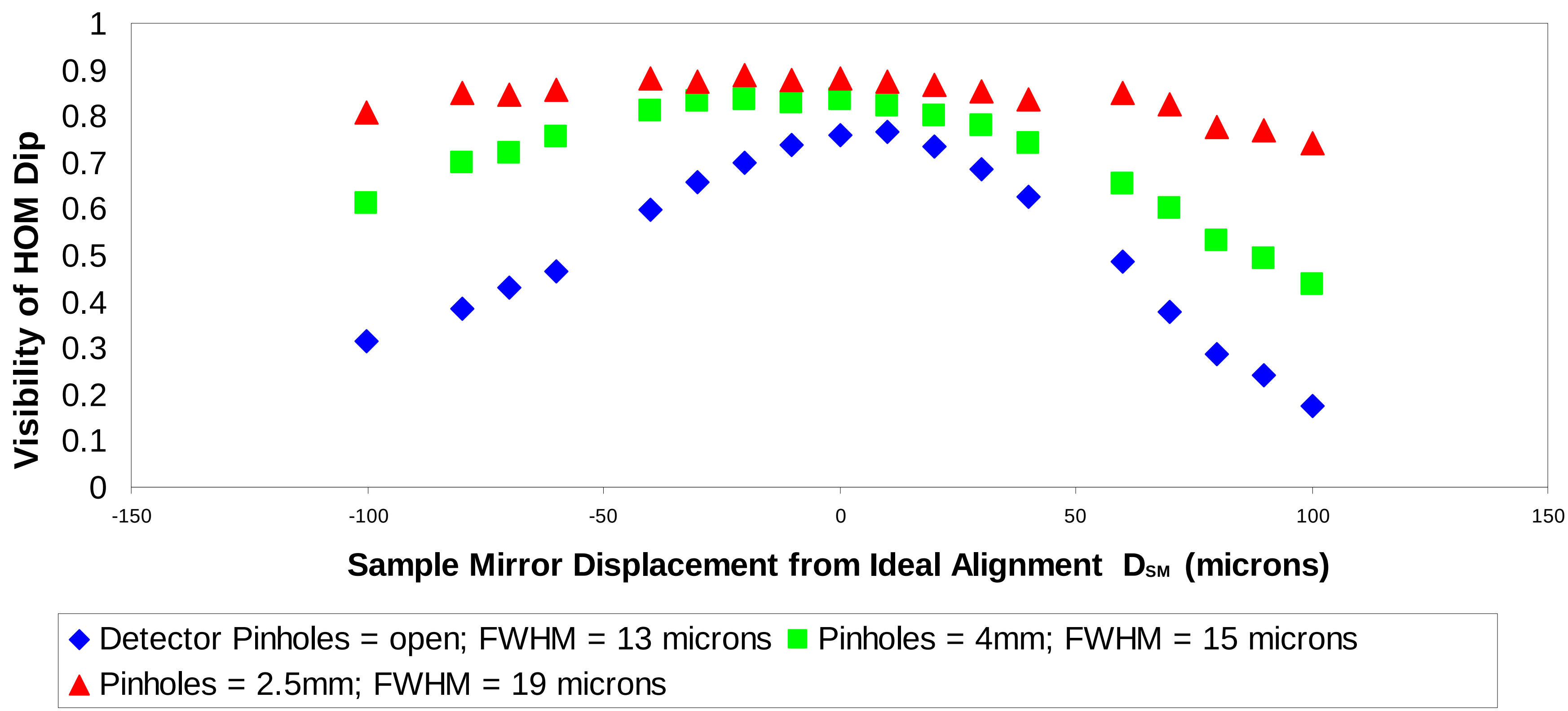
Compensation using two lenses in reference arm



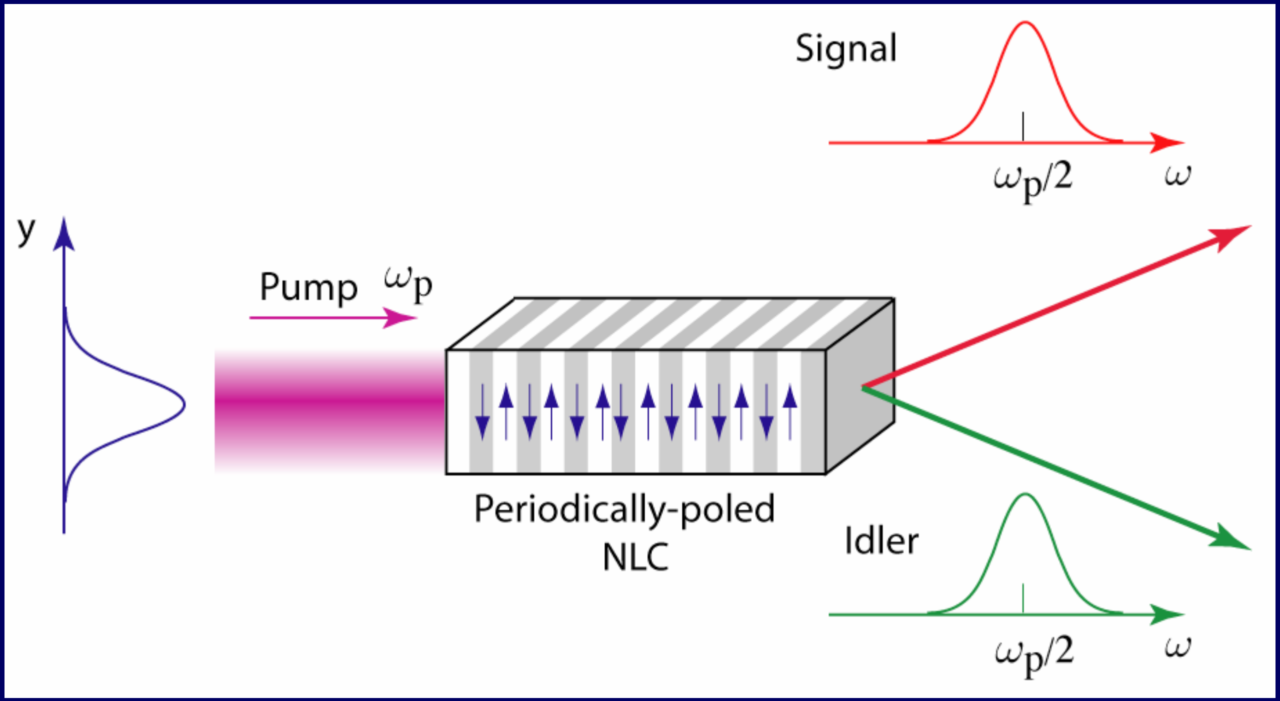
Depth of Focus



Variation of Axial Position of Sample Mirror in Dual 4-f Lens System in QOCT

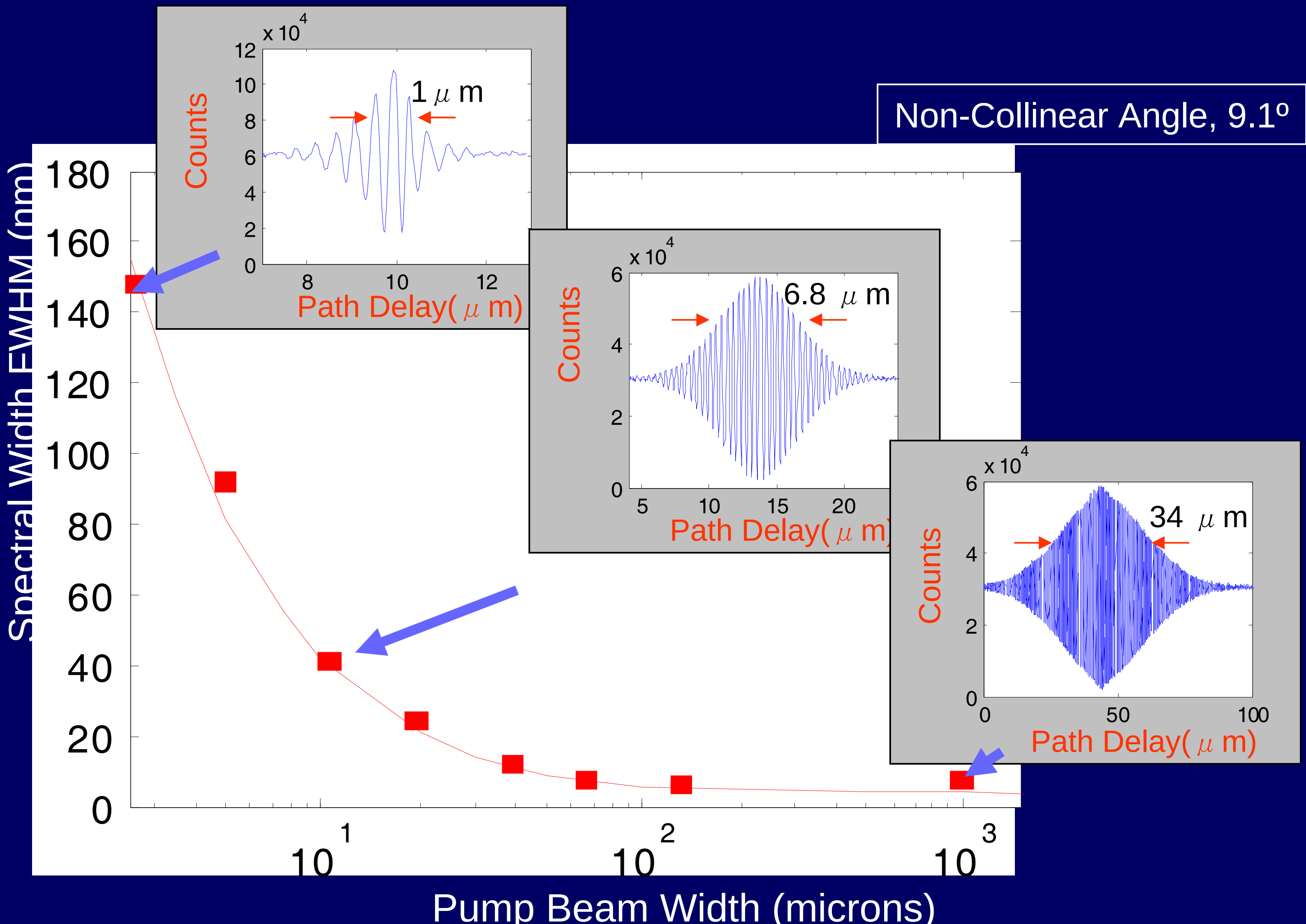


QOCT with Chirped-QPM Crystal



After Carrasco *et al*., *Opt. Lett.* **29**, 2429-2431 (2004)

Experimental Demonstration of Submicron OCT



The Promise of Q-OCT

- Q-OCT promises x2 improved axial resolution in comparison with conventional OCT for sources of same spectral bandwidth
- Self-interference at each boundary is immune to GVD introduced by upper layers
- Inter-boundary interference is sensitive to dispersion of inter-boundary layers; dispersion parameters can thus be estimated
- Preliminary experiments demonstrated viability of technique
- Technique can be extended to transverse imaging (Q-OCM)
- Technique can be extended to polarization-sensitive Q-OCT

Q-OCT: Challenges & Plans

- State-of-the-art linewidth is not sufficiently large (Axial resolution is only 19 μm).
- Two-photon flux is low. Duration of experiment is too long.

  A better 2-photon source is needed!

  Faster broadband single-photon detector is needed!

- Applications to scattering media (e.g., tissue). Theoretical & experimental research is necessary.
- Algorithms for data processing need to be developed.